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To assess the consequences of depletion of the ozone layer scientists and policy makers need information on the nature and magnitude of effects resulting from exposure to UV-B radiation. This information is critical to establishing responsible regulations and mitigation options.

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY'S STRATOSPHERIC OZONE RESEARCH PROGRAM

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INTRODUCTION

Overview of the Issue

The stratospheric ozone layer is the earth's primary shield against damaging ultraviolet radiation from the sun. However, certain man-made chlorofluorocarbon compounds (CFCs) and halons, upon migrating into the stratosphere, reduce the concentration of ozone. Chlorofluorocarbons also contribute to global warming, thereby altering climatic conditions. These halide compounds continue to increase in concentration on a global scale because of emissions from human activities, including use as refrigerants, foam products, aerosol propellants, fire extinguishants and solvents.

A major consequence of decreasing the ozone layer is an increase in the transmission of UV-B radiation (290-320 nm) to the surface of the earth. Researchers have identified many potentially serious effects of increased exposure to UV-B radiation on the environment and human health. These include: effects on agricultural crops, trees, and marine organisms, and damage to the human immune system, eyes (cataracts), and skin (cancer). Depletion of the ozone layer also contributes to materials damage, and affects ground-level air quality.

To assess the consequences of depletion of the ozone layer scientists and policy makers need information on the nature and magnitude of effects resulting from exposure to UV-B radiation. This information is critical to establishing responsible regulations and mitigation options.

Trace Gases Affecting Ozone

The natural distribution of ozone in the earth's atmosphere is not uniform. It is concentrated primarily in a thin layer in the stratosphere where it blocks most of the ultraviolet radiation in the 220- to 320-nm range, allowing only limited amounts of radiation in the 290-320 nm waveband (UV-B) to penetrate to the earth's surface. This radiation can be damaging to humans, other organisms, and man-made materials.

Many gases emitted from man's industrial and agricultural activities can accumulate in the earth's atmosphere and ultimately contribute to alterations in the vertical distribution of ozone. These gases accumulate in the lower atmosphere (troposphere) and then gradually migrate upward into the stratosphere where they contribute to depletion of stratospheric ozone. Less ozone in the stratosphere will result in a greater transmission of ultraviolet radiation to the surface of the earth, causing detrimental effects. Because of the long atmospheric lifetimes of CFCs and halons, scientists expect stratospheric ozone to continue to decrease into the middle of the next century even if emissions are curtailed worldwide.

Table 1 provides a summary of the major trace gases that contribute to ozone depletion, including their primary uses, atmospheric lifetime, and projected annual increase. Currently, the primary focus of regulations and mitigation options are on CFCs and halons.

EPA STRATOSPHERIC OZONE RESEARCH PROGRAM

EPA's Role

Three separate mandates require the U.S. Environmental Protection Agency to take a role in stratospheric ozone research: 1) the international Vienna Convention and subsequent Montreal Protocol, 2) the Clean Air Act, and 3) the Global Climate Protection Act. They also direct EPA to assist in developing international scientific assessments by providing information regarding the effects of stratospheric ozone depletion. In response, EPA has established an assessment-oriented research program on stratospheric ozone depletion to be conducted by the Office of Research and Development (ORD).

Increased UV-B radiation is a problem of global proportions. It is not an issue that the United States can solve unilaterally, but rather calls for a worldwide commitment to reduce production and consumption of ozone-depleting substances. EPA's research priorities reflect this international perspective.

The primary focus of the program is on the impact of UV-B radiation on natural ecosystems, the world's food supply, and human health. With this focus, EPA's program will provide important information from which to assess the global impacts of stratospheric ozone depletion -- information not only of domestic significance, but also of relevance to non-signatories of the Montreal Protocol. The results will provide scientific information to consider in the negotiations for the control of substances likely to be harmful to the ozone layer.

Program Goals and Strategy

A key challenge for EPA's Stratospheric Ozone Research Program is to target the available resources on areas of scientific uncertainty that are most useful to policy makers in addressing this issue. This work will contribute to the success of the Montreal Protocol and to compliance with the conditions of the Clean Air Act. For the conditions of the Protocol to be successful on a global scale, it is essential that researchers focus attention on areas that are relevant not only to the United States and other industrialized nations, but also to developing countries. EPA's research program is designed to play a significant role in generating scientific information that is credible and persuasive to these important audiences.

TABLE I. Trace gases affecting ozone concentrations and global climate change.

Trace Gas (Formula)	Primary Source	Ave. Life in Atmos.	ODP*	GP**
CFC-11 ($CFCl_3$)	Refrigerant/AC, Plastic Foams, Aerosols	75 yrs	1.0	0.40
CFC-12 (CF_2Cl_3)	Refrigerant/AC, Plastic Foams, Sterilants	110	1.0	1.00
CFC-113 ($C_2F_3Cl_3$)	Solvents	90	0.8	0.3-0.8
Halon 1211 (CF_2ClBr)	Fire Extinguisher	25	3.0	?
Halon 1301 (CF_3Br)	Fire Extinguisher	110	10.0	0.80
Carbon Tetrachloride (CCl_4)	Industrial Processes	67	1.1	0.05
Methyl Chloroform (CH_3CCl_3)	Industrial and Natural Processes	8	0.1	0.01
Nitrous Oxide (N_2O)	Fossil Fuels	150	--	0.016
Methane (CH_4)	Biogenic Activity, Fossil Fuels	11	--	0.001
Carbon Dioxide (CO_2)	Fossil Fuels	7	--	0.00005
Carbon Monoxide (CO)	Motor Vehicles, Biogenic Activity	0.4	--	--

* ozone depletion potential (CFC-11 = 1.0)

** greenhouse potential (CFC-12 = 1.0)

To comply with the conditions of the Montreal Protocol and the Clean Air Act, EPA acts as a lead agency in the United States to: 1) set research goals in response to policy issues regarding stratospheric ozone depletion, 2) coordinate research to accomplish those goals, and 3) synthesize the results of these research efforts. According to their missions, other federal agencies conduct specific research activities. EPA will continue to develop its in-house human resources and research effort to provide the appropriate guidance for design and analysis in each research area and to address the conditions of the Montreal Protocol in a timely fashion.

The research program places EPA in a position to evaluate overall policy implications from a scientific standpoint as research results become available. The program has been designed from the outset as an assessment-oriented effort, which provides results and information to use as input to the periodic assessments. The cooperation of other national and international organizations -- such as NASA, NOAA, USDA, NCI, NIH, DOE, NSF, WMO, WHO, SCOPE/ICSU, and UNEP -- is essential.

Research Framework

EPA's Stratospheric Ozone Research Program is structured around research questions that are explicitly relevant to policy decisions. Using the policy-relevant questions as the framework for the program provides the rationale for undertaking the specific research activities. The following questions are based on fundamental information needs:

1. How widespread are the potential effects of UV-B radiation? What populations, systems or substances are at greatest risk?

An increase in UV-B radiation will continue to exert some degree of influence on man and the environment for the foreseeable future. This stress will transcend regional and national boundaries, having effects on widely separated ecosystems and populations. These two attributes make understanding the effects of UV-B radiation on human and other biological systems of critical importance.

2. How intensive are the effects of UV-B irradiance? What are the doses that would pose a significant risk?

The response of biological systems to UV-B radiation may differ significantly for different life stages of the same species as well as by latitude and season. What are the specific dose-response relationships, and what mechanisms are involved? Identification of basic and common mechanisms of damage will allow extrapolation of dose-response models to other systems not yet studied.

3. If the exposure to UV-B radiation is reduced, what is the anticipated rate and extent of recovery of sensitive systems?

Organisms and ecosystems generally (but not always) recover from environmental stress. It is important to know to what degree and at what rate individual organisms and ecosystems can repair the damage inflicted by enhanced UV-B irradiance. In managed ecosystems (agriculture and silvaculture), UV-B tolerant species may be used to replace less tolerant species. In natural ecosystems some species may be able to adapt over time to increasing UV-B irradiance.

4. What interactions occur between increased UV-B radiation, global climate change and atmospheric pollutants?

The composition of the atmosphere depends to a large degree on natural and man-made emissions, including the emissions of greenhouse gases such as carbon dioxide, CFCs, methane, and nitrous oxide. If new data suggested that increasing UV-B radiation would alter biogeochemical cycles involving these chemicals and result in a disruption of ecosystems or change in global climate, additional regulation to protect the stratospheric ozone layer may be necessary.

5. What mitigation options can be applied? To which systems?

Chemicals with less ozone-depleting potential can be used as alternative substances, such as for aerosol propellants. But acceptable substitutes are not currently available for most ozone-depleting compounds. Recovery and reuse of substances also is a viable option. In addition mitigative responses to the effects of UV-B radiation also need to be investigated, including the replacement of sensitive strains in managed systems with more UV-B tolerant strains. Options relevant to the human system are more tenuous and need to be investigated, as well.

Critical Program Elements

The work proposed for the EPA's Stratospheric Ozone Research Program is based on the following critical elements:

Build Upon Existing Knowledge. The research program is designed to build upon the base of knowledge and experience already accumulated by scientists in the United States and other interested countries. Coordination will be maintained and strengthened between federally funded research and international efforts. Available research results will be used to provide guidance in the design of future research and monitoring efforts.

Establish Long-Term Monitoring Network. Researchers need quality-assured monitoring data to determine the empirical relationship between the ozone layer and levels of UV-B radiation at the earth's surface. The results from current monitoring efforts worldwide have yielded conflicting results. A "status and trends" network will be established under this program to determine the actual dose of UV-B radiation at ground level and to monitor variations in total column ozone over an extended period of time. This effort will be coordinated with the EPA/ORD Global Climate Change Program, as well as with other federal agencies and international organizations.

Conduct Research to Reduce Key Uncertainties. The program is intended to increase our understanding of the potential consequences of ozone depletion. Both extensive and intensive studies will be conducted. The emphasis of the proposed research is on activities that will help assess the global impacts of increased UV-B radiation and establish a firmer basis for decision making. The priority research areas address EPA's responsibilities under current mandates.

Investigate Engineering Alternatives and Solutions. The research program will include investigations of technological solutions to some of the problems faced in combatting the thinning of the ozone layer. Alternatives to the most damaging CFCs is one area for research and a fuller understanding of nitrous oxide emissions is another.

Transfer Information to the International Community. EPA will make results from its program available to all interested parties in an effort to encourage international support for controlling the substances that deplete the ozone layer. Information from EPA studies on the world's food supply and human health will be especially important for developing countries.

Evaluate Information Periodically. Results generated by EPA's program and other research in the United States and abroad will add rapidly to our knowledge of the effects of stratospheric ozone depletion. Periodically, the information will be synthesized, subjected to scientific peer review, and interpreted to guide decisions on future research and policy. EPA will contribute to the international scientific assessments (1990, 1994, etc.) mandated by the Montreal Protocol.

The following section describes the research strategy for attaining the stated goals and objectives, based on these fundamental principals, and defines EPA's research priorities.

MAJOR RESEARCH AREAS

With the limited initial funding of EPA's Stratospheric Ozone Research Program, it is not feasible for EPA to study the full range of potential effects from increased UV-B radiation. Rather, EPA will focus its efforts on areas of primary importance to the mission of the Agency, building upon the strengths of other national and international organizations.

In the proposed program, EPA will place highest priority on areas of research that will provide information relevant for decision making during the next decade. In addition, EPA has adopted a global rather than strictly national focus in establishing priorities. This work can provide new insights in time for the international scientific assessments prescribed by the Montreal Protocol.

Of particular interest to EPA is the impact of UV-B radiation on two areas: ecosystems directly related to the world's food supply, and human health. In addition, EPA will investigate engineering and technological aspects of the man-made gases that contribute to the thinning of the ozone layer. Research priorities within these broad areas are defined as follows:

- Terrestrial Ecosystems -- Wetland Rice, Biogeochemical Cycles
- Aquatic Ecosystems -- Marine Fisheries, Biogeochemical Cycles
- Engineering -- CFC Replacement, Nitrous Oxide Processes
- Human Health -- Immune System, Infectious Diseases

These four areas will be the primary focus of both intensive and extensive studies under the proposed program. EPA will conduct supporting studies to monitor the dose of UV-B radiation at ground level relative to these important systems.

Terrestrial Ecosystems

The primary focus of EPA's Terrestrial research is on the effects of UV-B radiation on the wetland rice ecosystem. Rice was selected as the crop for study because of its significance as a major source of food, and its role in the generation of greenhouse gases, which affect stratospheric ozone and influence climatic conditions. Rice ecosystems are a significant source of methane and nitrous oxide.

No crop is likely to supplant rice in terms of global importance well into the next century, and probably beyond. The three basic types of rice ecosystems (irrigated, rain-fed and dryland) together are responsible for about two-thirds of the calories available to mankind worldwide. Due to the relatively

greater productivity potential, acreage devoted to irrigated and rain-fed (i.e., wetland) systems is increasing faster than acreage devoted to dryland growing conditions.

Of the rice strains or cultivars studied, 40% appear to be sensitive to UV-B radiation. However, the number of cultivars sampled has been quite small. New lines have been developed at several research facilities, including the International Rice Research Institute in Los Banos, Philippines; and the USDA breeding/genetics facility in Stuttgart, Arkansas. These cultivars are being made available to farmers worldwide, and are expected to be used on a substantial portion of the acreage in developing countries well into the next century. These new lines have substantial genetic differences from cultivars released a decade ago, and therefore, need to be examined to determine their sensitivity to UV-B radiation.

Effects on Wetland Rice Ecosystems. EPA proposes to investigate the nature, magnitude and extent of increased UV-B radiation on wetland rice. This research will address all five policy-relevant questions described earlier. The specific objectives include the following:

- Determine the impact of increased UV-B radiation on yield;
- Determine the effects of UV-B irradiance on the generation of methane and nitrous oxide;
- Determine the sensitivity of major rice cultivars to changes in UV-B exposure, temperature, and atmospheric carbon dioxide;
- Determine the capability to extrapolate conclusions drawn from wetland rice ecosystems to wetlands in general, and from wetland rice systems to dryland rice systems; and
- Establish ground-level monitors at each research site to record the current dose of UV-B radiation and determine trends over time.

The proposed research will be conducted through a series of studies on: 1) sensitivity, 2) dose-response, 3) mechanisms, and 4) interactive effects.

A range of rice cultivars will be examined to determine their sensitivity to UV-B exposure. The cultivars selected will represent a diversity of lines and include those cultivars most commonly grown. Crop growth and development, and the impact on the generation of methane and nitrous oxide, will be the primary measure of sensitivity, allowing short-term growth analysis experiments to be utilized. A limited range of UV-B radiation

treatments will be employed, representing small, moderate and worst-case ozone depletion scenarios.

To study dose-response relationships, a minimum of two rice cultivars, representing sensitive and resistant types, will be selected based on the results of the sensitivity studies. These cultivars will be subjected to a minimum of 3-4 years of field studies to examine specifically the effects of UV-B radiation on yield and quality. The mechanisms of UV-B radiation insult and the plant resistance will be investigated using the same sample populations and exposures as in previous steps. The parameters will include measures of photosynthesis, respiration, cell membrane integrity, DNA effects, and carbon allocation patterns.

EPA will investigate possible interaction of temperature and carbon dioxide for rice cultivars. Research will employ the same sensitive and resistant cultivars used in the previously described UV-B studies.

Output: Better understanding of the effects of UV-B radiation, temperature, and carbon dioxide enrichment on rice cultivars. This information will serve as input to determine the potential impact on the world's food supply.

Aquatic Ecosystems

The purpose of the Aquatics research is to determine the direct and indirect effects of UV-B radiation on commercially important marine fish species, as determined in economic (fraction of gross national product) or dietary (fraction of protein intake) terms. EPA designated marine fisheries as a high priority area because of the significance of fish as a global source of animal protein. Research also will focus on the effects of UV-B radiation on biogeochemical cycle and linkage to the marine food chain. The specific objectives of this research include the following:

- Determine the impact of increased UV-B radiation on components of the marine ecosystem and on food productivity;
- Determine the impact on the role of marine ecosystems in biogeochemical cycling (e.g., will increased exposure of phytoplankton communities to UV-B radiation have an impact on global carbon cycling? on dimethyl sulfide production?); and
- Determine the status and trends of UV-B radiation at the ocean surface.

The same four-step process that was outlined for the research on terrestrial systems will be used here: studies on sensitivity, dose-response, mechanisms, and interactive effects.

Three research areas are proposed for the initial focus of the Aquatics program: 1) direct effects of UV-B radiation on the early life stages of fish, 2) indirect effects on the marine food web, and 3) effects on the role marine microbes play in biogeochemical cycling. An understanding of the effects of UV-B radiation on these systems will provide a solid foundation for assessing global risks and impacts, and the basis for extrapolating results to untested systems and ozone depletion scenarios.

Direct Effects on Early Life Stages of Fish. Initial sensitivity screening studies will examine the eggs and larvae of five to ten species of fish, selected by both ecological and societal criteria. One species then will be selected as a model for intensive studies of dose-response, adaptation and repair mechanisms, and interactive effects. Criteria for selection include: sensitivity, geographic distribution, economic importance, vulnerability of life stages to UV-B radiation, practicality for laboratory exposure experiments, and quality of previous studies. The responses of natural fish populations to increased UV-B radiation will be estimated from comparisons of results from: laboratory dose-response studies, field studies of the penetration of UV-B radiation into marine waters, and field studies of the vertical and latitudinal distributions of fish eggs and larvae.

Output: Dose-response information on the effects of UV-B radiation on sensitive, early life stages of important marine fish species.

Indirect Effects on the Marine Food Web. Planktonic food webs are critical to the success of the early life stages of most fish species. The proposed research will examine the effects of UV-B radiation on marine plankton communities and subsequent effects on the fish population studied above. Changes in composition, standing stocks, and production of phytoplankton communities in response to UV-B radiation will be determined through laboratory studies and mesocosm studies. The response of natural phytoplankton populations to UV-B dose will be estimated from comparisons of these experimental results with current and projected future intensities of UV-B radiation in marine waters. Field and laboratory studies will be conducted to determine the impact of changes in phytoplankton communities on the growth and production of fish prey stocks.

Output: Estimate of the effects of UV-B radiation on plankton species density, species composition, food quality for fish, and efficiency of trophic energy transfer.

Effects on Biogeochemical Cycling (Marine). Inhibition of marine microbial activity by increasing UV-B radiation could have important consequences for several global biogeochemical cycles.

Marine microbes play a critical role in the global exchange of elements and compounds between the earth's atmosphere and hydrosphere. For example, phytoplankton photosynthesis in the upper layer of the oceans provides a sink for about 80% of the man-made CO_2 released to the atmosphere. The only significant source of sulfur (dimethyl sulfide) to the atmosphere (and subsequent oxidation to SO_2) is a result of microbial activity. Research is needed in this area to determine: 1) the penetration of UV-B radiation through ocean surface waters, 2) the vertical distribution, residence time, and activity of phytoplankton and other marine microbes within the UV photic zone, and 3) the effects of enhanced UV-B radiation on important biological processes.

Output: Information on the impact of UV-B radiation on the role of marine ecosystems in biogeochemical cycling, and its potential impact on global climatic change.

Effects on Other Aquatic Systems. In addition to these three priority areas, EPA has identified several other important systems to study if time and resources allow. Research plans in these areas will be determined based on the results of preliminary scoping studies. Suggested research topics include the following:

- Coral Reefs. These ecosystems support a diverse community of marine biota and may be sensitive to UV-B radiation. Studies are needed to determine the effects of UV-B radiation on the survival and growth of selected coral systems.

- Marine Macrophytes. Sea-grasses/seaweeds are an important shallow water food resource in both temperate and tropical regions and are potentially sensitivity to UV-B radiation. Research is needed to determine UV-B radiation effects on photosynthesis and growth of sea-grasses.

- Polar Ecosystems. Stratospheric ozone depletion is particularly pronounced at higher southern and northern latitudes, resulting in increased UV-B radiation reaching the surface. Existing information on the effects on antarctic ecosystems needs to be synthesized; accepted protocols for marine research need to be established.

- Freshwater Ecosystems. Freshwater fisheries provide a significant proportion of food in some countries (e.g., China), and blue-green nitrogen fixing algae are important to paddy rice production. The potential effects of UV-B radiation on these systems need to be examined.

- Wetlands. These ecological important systems contribute to biogenic emissions of methane and nitrous oxide, and provide

a linkage between terrestrial and aquatic systems. Research on the effects of UV-B radiation will be coordinated with EPA's wetlands research program.

Engineering

The engineering component of the Stratospheric Ozone Research Program will have two project areas addressing CFC, halon, and nitrous oxide engineering research: 1) insulation foam and 2) nitrous oxide combustion source budgets.

- Insulation Foam. The need to find substitutes for the most damaging CFCs is paramount. A better understanding of the engineering of improved thermal efficiency for insulating foams could lead to alternative chemicals to use as blowing agents. The research program will strive to determine the key properties of new chemicals and to elucidate their end-use characteristics.

- N_2O Combustion. EPA will conduct field tests using on-line N_2O analyses of carefully selected advanced and conventional combustion sources that are identified from preliminary screening analyses.

Human Health

In the Human Health area, EPA has given highest priority to studying the effects of UV-B radiation on the immune system and infectious diseases because of the lack of an established data base and the significance of these effects in both developed and developing countries. Skin cancer receives a lower priority (than is warranted on a domestic level) because of its established data base and because it is primarily a disease of light-skinned Caucasians, a minority population worldwide. The following research objectives have been identified:

- Assess the nature, extent and potential clinical relevance of immunosuppression induced by UV-B radiation in normal human subjects;

- Determine whether pigmentation of the skin influences susceptibility to UV-B induced immunosuppression;

- Examine the relationship between the dose of UV-B radiation and the response in humans; and

- Determine the effects of UV-B exposure on the incidence, severity and recurrence of a spectrum of infectious diseases.

These research activities will be coordinated closely with the U.S. Department of Health and Human Services including the relevant National Institutes of Health (NIH), and with efforts

sponsored by the World Health Organization and other groups. The results generated from this work will contribute important information to all five Policy-Relevant Questions. The following work is proposed based on areas of existing research and discussions with a number of leading experts:

Effects of UV-B Radiation on the Immune System. UV-B radiation, which is an immunosuppressive agent, can induce local and systemic effects on the immune system depending on the dosages. Animal and human experiments have indicated that the dosages needed to achieve local or systemic effects could be received by human populations under normal exposure conditions. At present, however, there is no information that allows a quantitative assessment of the possible adverse effects that might arise from such immunosuppression.

Effects on Infectious Diseases. Potential impacts of UV-B radiation on infectious diseases are of major concern. EPA has given highest priority to funding pilot studies of animal models of infectious diseases. Extensive studies will evaluate a number of different systems to determine if there is an effect, and intensive studies will determine the mechanism of effect in systems where an impact has already been demonstrated. In these systems, epidemiologic studies also will be considered to evaluate the correlation of human disease with exposure to sunlight (e.g., onset of epidemics, incidence and/or severity of the disease, vaccination failures).

Other Human Health Concerns. Other important research areas have been identified but they have been assigned a lower priority either because of their less-than-global focus or because existing research is underway. Such topics include the following:

- Skin Cancer. While this area has been well studied, there are still some major areas of uncertainty. Recommended are specific activities to refine estimates of risk and to develop better explanations of the mechanism of UV-B induction of skin cancer.

- Ocular Effects. Research in this area has been limited. Studies are needed to investigate the role of UV-B radiation in eye damage, including the exacerbation of cataract formation. The action spectra for various types of ocular damage also need to be defined.

- Acid Aerosols. Another area of potential research relates to the health effects associated with ground-level ozone concentrations and acid aerosol formation, both of which are exacerbated by increased UV-B radiation.

Summary

In these major research areas, standardized procedures and explicit quality assurance protocols will be followed. EPA understands the importance of scientific rigor in maintaining credibility, especially for an international research effort. With this design, the program will contribute significant information from which to assess the global impact of stratospheric ozone depletion.